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THERMONUCLEAR REACTIONS THROUGH LASER RADIATION OF FUSION MATERIALS

E. Witalis

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ABSTRACT. The use of lasers for fusion weapons as well as for hydrogen energy is discussed. Criteria for an exothermic laser induced fusion process are formulated. An account of known calculations and estimations show that the existing laser systems are several magnitudes too small for direct use in fusion weapons or for peaceful use of hydrogen energy. However, it is shown that in combination with well established methods, generation and testing of a plasma with laser radiation would be feasible. Finally, the fields within laser and plasma physics in which important developments of laser-induced fusion processes can be expected are given.

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/1

Summary

This report provides, in elementary form, a description of the technological and scientific background for the use of lasers both in fusion weapons and for peaceful hydrogen energy. This subject has frequently been reported on in the popular press. The introduction mentions the more important source materials for the report. The report then describes the sectors of modern laser development which have important fusion applications. It is then argued that the possibilities are relatively slight for developing fusion processes by means of focused laser radiation of neutral gases as compared with those possibilities afforded by focusing such radiation on solid fusion materials, especially when these are in the form of small particles.

The "trigger condition," i.e., the criterion for an exothermic laser-induced fusion process, is formulated, and subsequent material on previously known calculations and evaluations indicates that performances of present laser systems are too poor by several orders of magnitude to permit direct use of lasers in fusion weapons, and that this is true to an even greater degree in the production of hydrogen energy. On the other hand, it is shown that laser radiation can, in combination with well-known methods, be of great value in the field of hydrogen power research, plasma generation, and plasma heating. Finally, those areas of laser and plasma physics are described in which important developments may be expected as regards laser-induced fusion processes.

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TABLE OF CONTENTS /2*

*Numbers in the margin indicate pagination in the foreign text.

1. Introduction /3

The press, in the last two years, has carried stories and articles with such sensational headings as "A Laser Trigger for H-Bombs" [1], "French General Sees Possibility of Cheap H-Bomb" [2], "How to Light a Mini-H-Bomb [3], etc. The background for all of this is a relatively new technique utilizing very short, but high energy light pulses by means of special laser systems. These pulses can be focused by simple optical means to produce a "burning point" containing unimaginable energy density. The temperature needed for fusion processes can be reached within a small area, and, further, if the initially developed fusion energy is deposited around the burning point in a manner suitable for temperature increase, the fusion process can, in principle, spread over a larger area than that which was originally irradiated.

The present report compiles in elementary form the available published information, as well as data procured by other means which relate to known experimentation and theoretically calculated possibilities for the development of fusion energy through laser pulse radiation of fusion materials. Many important data, to be described later, were obtained during a study trip in September 1970. The author is deeply grateful in particular to two experts, Dr. Robert L. Hirsch of the U. S. Atomic Energy Commission, and Prof. Dr. S. Witkowski of the Institut fur Plasmaphysik in Garching, and is indebted to them for the opportunity to discuss the subject with them and for access to reports not publicly distributed. Included among the most important published works of a general nature used in the present paper were R. Holcomb's "Plasma Heating with Lasers" [4], "Laser and Thermonuclear Fusion" by S. Witkowski [5], "Fusion of Light Nuclei Under a Laser Beam" by F. Floux [6], and C. G. Young's "Glass Lasers in Thermonuclear Research" [7].

2. Development of Lasers for the Generation of Fusion Plasmas

The development of lasers for fusion purposes during the 1960's was directed mainly toward increasing the volume of energy in the emitted pulse and simultaneously shortening its length. The following are the four most important steps in this development. /4

a. Q-switching. The simplest fixed laser functions such that the light from a flash tube raises the atoms in a rod of suitable material to a level of energy excitation. The ends of the rod are reflective so that the emitted light, which is reflected between them, stimulates even more atoms. This process continues until the number of atoms which have reverted to their base state is so great that additionally stimulated emission is hindered. The resulting laser pulse has an energy of the order of several watt-seconds, and a length of a few or of several hundreds of microseconds. Q-switching, which was introduced in 1962 by McClung and Hellwarth [8], is a method for retarding emission until the flash tube has stored a much higher number of atoms in an excited state; it is most easily accomplished by replacing one of the rod reflecting end surfaces with a movable mirror. When the mirror is turned in its reflecting position, one obtains a so-called super or giant pulse with an energy of the order of several watt-seconds, but with a pulse length shortened to approximately 20 nanoseconds.

b. Mode locking. The continued development which led to the so-called second generation lasers had as its origin a new method, mode locking, for shortening the pulse length. By utilizing the non-linear optical characteristics of certain color elements, it was possible for de Maria et al [9], and other groups of researchers, to prove that the relative phase conditions in the frequency modes ($\nu_N = N\nu_o$), which occurs in the laser could be fixed. N is a large integer and ν_o is the lowest resonator mode. Locking of the phase levels is accompanied by the joining of the modes to a train of short pulses, superimposed on the main pulse. A special arrangement makes it possible to select an individual short pulse which, while it only has an energy of several millijoules, has a length of a few picoseconds.

c. Cascade coupling of lasers. In principle, there are no diffi- /5
culties in using a weak pulse to stimulate emission in a rod having excitated atoms. The energy thus released is then added to that of the incoming pulse and, further, if the energy release takes place mainly near the front of the resulting, amplified, incoming pulse, it can become shorter than it was originally.

d. New laser materials. The possibility of such cascade coupling over many stages is limited by electromechanical strength. The transition from rubies to other materials, especially the neodymium-coated glasses, provides for greater rod dimensions and therefore greater energies. The strength is, however, critically dependent on a high degree of cleanliness and the presence of even small quantities of certain trace elements, especially platinum, or ceramic contamination stemming from the casting, will significantly increase the risk of a break. An early, and inclusive, study under the aegis of the Commissariat de l'Energie Atomique in France resulted in French dominance for several years in the field of neodymium-coated high effect lasers with glass qualities which had up to 40 Joule pulse energies per cm^2 of emitting surface. It would now appear that the Americans (American Optical, Owens) and Germans (Schott) are on a par with the French.

The limited strength of the glass can be compensated for in part by greater dimensions of the rods in the final stage of the amplifier. One difficulty that arises is that the optics pump large volumes. Another is that of cooling and casting glass weighing one or two kilograms. The problems can of course be avoided by parallel laser systems or, more sophisticated, by replacing conventional rods with a number of plates set up on a slant, as done by Kidder [10] in Livermore.

3. Radiation of Fusion Material in the Form of Neutral Gas /6

By using the above-described mode locking technique and amplification methods, it is possible for the effect for picosecond pulses from neodymium-glass lasers to reach in excess of 10^{12}W. If this radiation is focused on a burning point with a diameter of 0.1 mm, the effective flow has a density of approximately 10^{16}W/cm^2, which corresponds to an effective density in a light beam where the electrical force field is in excess of 10^9V/cm. When focusing in a gas, as in air, for example, there is developed a non-stationary electrode discharge, the so-called laser spark. This phenomenon was observed as early as 1963, during the first experiments with Q-switching, but was at that time considered to be an interesting and amusing detail. Thorough quantitative research during subsequent years showed, however, that the laser spark actually was identifiable with a major, complex problem which has yet to be explained in complete detail. Of special quantitative, theoretical interest is the observable multiphoton effect when the gas is ionized [11], with the result indicating that the first freed electrons must have been formed by the simultaneous absorption of a number of photons by one atom, because the energy of the individual photon, 1.8 eV for the ruby laser, is only a fraction of the needed ionization energy. Ionization continues, except in extremely rarefied gases, in the form of the familiar inelastic electron shocks and snowballing phenomena in the strong electric field of the focal point, and leads to the creation of a limited volume with partially, or totally, ionized plasma. The highest temperatures hitherto measured in laser sparks are of the order of one or two million degrees [12], and thus are lower than the temperatures necessary for fusion processes, with more than one order of magnitude, approximately 10^8 °K. It does not seem possible to increase the temperature of the laser spark much more by increasing pulse energy, because this would lead primarily to a greater expansion of the plasma volume without significant rise in temperature. The expansion stages of laser sparks also have been studied in great detail [13], and show many similarities, particularly the gas dynamic effect of radiation ("radiation supported shock wave") with atomic weapon effects.

/7

Naturally, it is possible, in principle, for focused laser radiation of neutral fusion gas to lead to thermonuclear reactions, if it is assumed that plasma expansion is retarded, for example, by strong magnetic fields, and by extending radiation time until thermonuclear temperature is reached by the absorption of the laser beam. There is, however, a critical electron density in a plasma, and this must be exceeded to permit absorption of electromagnetic radiation of a given frequency. This critical density is $3 \cdot 10^{21}$ cm^{-3} for a ruby laser, corresponding to an original neutral gas pressure of about 100 atm. At the very least, this may well be said to be a very depressing description of the surroundings of a thermonuclear plasma, but it still is modest when compared to the force of the magnetic field required to contain a plasma of the required density and thermonuclear temperature. The critical electron density may be reduced by substituting laser beams with lower frequencies, and it also may be conceivable that it can be reduced further, because absorption takes place in many stages between reflections of the light. Even with these qualifications, however, fusion projects based on external magnetic containment of optically heated laser sparks must be considered unrealistic.

Expansion in a laser spark is not symmetrical, but is greatest in the direction of the incoming light cone. A very brief, recently published proposal [14], is based on the concept of masking the central part of the focusing lens so the resulting light cone becomes a tube converging at the focal point. Highly oversimplified calculations (in cylindrical geometry!) have been used to argue that the implosion development toward the tube's axis should make thermonuclear conditions possible there. There is no evaluation of available laser performance, nor is there indication of any experimental testing of the concept, although there is a suggestion by the author, very prominent in his field, that can be interpreted as meaning that the proposal will result in advantages, already known to exist, when laser pulses are focused on solid fusion material.

4. General Comments on Radiation of Solid State Fusion Material

/8

When a small particle, solid dueterium for example, is freely suspended in a vacuum and is hit by a high energy focused laser pulse, it is converted to a plasma, but, as distinct from the previously described laser spark in neutral gas, the plasma volume is determined by the original size of the particle and the sluggishness of the expansion progression. In general, therefore, increased laser effect and energy bring higher plasma temperature and, in principle at least, there is no difficulty in reaching fusion requirements. The first, and rather rough, calculations made regarding this method of creating fusion plasmas were published in 1964 by Dawson [15] and, independently of him, by Basov and Krokhin [16]. The starting point of their simplified theoretical models is a totally ionized plasma with spherical, symmetrical, expansion and homogenous total absorption of the incoming laser light to the point where expansion has resulted in the absorption length of the light being in excess of the diameter of the plasma. These calculations thus did not consider the extremely complicated initial phase in the formation of the plasma especially the dynamics of the absorption stages. For this reason, the calculations are reliable only as an approximation of the minimum effect and energy values required to attain fusion conditions. The results showed that deuterium spheres with a diameter of 60-600 μ could reach a temperature of approximately 10^7 $^{\circ}$K using laser pulses with energies of 1-10^3 W-sec developed over a period of 10^{-10}-10^{-9} sec.

5. Theories Concerning Laser-Induced Fusion Processes

Fusion material usually is a combination of equal parts tritium and deuterium in the form of a small, solid particle, which naturally, as in the case of atomic weapons, can be enclosed, partially or totally, by a tamper. The particle is heated rapidly to thermonuclear temperature by one, or several, synchronized laser pulses with a resultant energy development through nuclear reactions to a point where it is Q_{FL} times as great as that which can be supplied by laser light. Disregarding weapon and "plowshare" uses, the released energy must be converted with the aid of a surrounding "blanket," possibly reactive to tritium, and a system for the conversion of heat to /9
electricity. Some of the electrical energy thus developed can be utilized to excite the laser system before the next pulse.

A refined arrangement, called "Blascon," for containment of laser-induced detonations has been suggested by A. P. Fraas [17]. Briefly, it consists of an axially rotating hollow cylinder partially filled with liquid lithium. The particle with the fusion material is located in the middle of the cylinder, and the lithium contains externally introduced gas bubbles so the shock wave following the explosion is converted to heat by compression. There also is a heat-producing retardation of the fusion fragments within the lithium and the "breeding" of tritium, which is extracted in the circulation process used to convert heat into electric energy.

The following three parameters are fundamental for the evaluation of each project of the types mentioned:

1. the energy balance, as defined by $Q_{FL} = 1$, which means that the energy from the nuclear reactions will equal that developed by the laser light (note that the necessary pump energy to the laser is much greater);

2. the maximum energy that can be contained, or, in other words, the requirement that there be a controlled and a convertible fusion process;

3. the cost of the entire system.

Laser experts now seem to be in complete agreement that the energy feeding of the particle must take place within 10^{-9} second, or less. Short pulses such as these can be attained without difficulty by using existing glass lasers and mode locking. The main question, therefore, is the pulse energy.

Subject to modifications as a result of laser development in 1970, the following representative values for laser performance are applicable:

USA-Sandia: 80 W-sec at $2\text{-}10 \cdot 10^{-12}$ sec; /10

USA-University of Rochester: 200 W-sec at 10^{-10} sec;

France-CGE: 250 W-sec at $5 \cdot 10^{-9}$ sec.

The necessary energy balance calculations have yielded very different answers. Those by Tuck [18], concerned solely with orders of magnitude in the case of the tamper, yielded a minimum of 10^5 W-sec, whereas a later, and more detailed, calculation by Lubin [19, 21] resulted in a figure several times 10^7 W-sec. An earlier calculation by Haught [20, 21] for a system without tamper showed that the balance required more than 10^9 W-sec, and experts such as Kidder [21] and Dawson [21] are reported to have agreed with this result while noting that a reduction by a factor of about one hundred was possible by the use of tamper and magnetic reduction of heat losses. The data cited above are concerned with the "trigger requirement," so far as can be ascertained, in that the high-energy fusion fragments formed originally are to meet after their release, and, through collisions, slowed down by a sufficient quantity of material so that an effective temperature-increasing energy deposit can occur. The probability of collisions is greatly reduced during the thermal expansion of the particles, and since only mechanical inertia of the fusion material retards the expansion, there is a resulting need for an extremely rapid supply of laser energy.

Witkowski [5] has calculated the minimum energy of the laser pulse on the basis of other, and probably more conservative, assumptions. Before a thermonuclear fusion reaction takes place, the two reacting particles have taken a "random walk" caused by a large number of elastic shocks. In practice, the distance between the beginning and end points for such a process is not equal to zero, but is a finite value that can be calculated and which provides a measurement for the required minimum dimensions of the fusion plasma in order that a given fusion effect can be caused. Witkowski's calculations further assume that the plasma expands at thermal speed, but maintains a constant temperature as a result of the fusion energy developed, although without utilizing the previously mentioned "trigger condition." Instead, the $Q_{FL} = 1$ requirement is used. In other words, the theoretically maximum development of fusion energy must reach the level of the heat energy from the laser light initially required for overall fusion to begin. This requirement leads to the necessity for a minimum diameter of 1.5 cm as the original size of the radiated particle, implying a laser energy of $4 \cdot 10^8$ W-sec to make the transition to thermonuclear conditions. It is interesting to note that Witkowski's calculations yield about the same results as those of the Americans, both as to laser energy and particle size. Haught [21] shows a minimum diameter of 1 cm for a D-T particle, and at the same time states that the gain in laser pulses shorter than 10^{-9} sec is then insignificant. /11

The data on the maximum energy conforming to the containment requirement, point 2 above, are extremely uncertain, but one can assume extremely severe technical difficulties in dealing with energies exceeding $5 \cdot 10^8$ W-sec, the equivalent of 100 kg of explosives. What follows then is that if the high values calculated by Haught, Witkowski, and others are accepted as accurate, there is no possibility of developing a practical fusion reactor through the effect of focused laser radiation on particles of fusion material. On the other hand, _if_ the calculations which arrived at 10^7 W-sec for $Q_{FL} = 1$ are correct, and _if_ the fusion energy so developed should later be greatly increased by higher energy supply, an interval of 10 to 100 should exist between a lower limit provided by the equilibrium condition and a corresponding upper one derived from the containment condition.

Recalculated in terms of effect, 10^7 W-sec per nanosecond provide a mean effect of 10^{16} W in the laser pulse. This exceeds that which can be attained with present lasers by a factor of 10^5. It hardly seems possible that a laser system capable of such performance will be developed within the foreseeable future and, even if it should be developed, there remain two complicating factors. First, one must consider the limited recovery period between pulses in a pulsing fusion reactor. The "Blascon" project shows 10^9 W-sec every tenth second, which results in an average end effect of only 100 MW. Second, the effective level of laser systems must be raised radically from the present /12 figure of approximately 0.1 percent using pulse neodymium-coated glass lasers. This low value is not at all true of carbon dioxide lasers which have demonstrated effect levels of approximately 20 percent, but here mode locking injects special difficulties. The necessarily very short pulse lengths are difficult to attain, and the opinion even has been expressed [22a] that the narrow band width of carbon dioxide lasers makes short pulses impossible.

Calculations [21] made with respect to point 3 above, the cost of electric power generation by the use of a pulse laser-fusion system, are so speculative that they have no great value. A factor of 10^3 has been cited as the relationship between present and needed reduced costs. This factor is to be compared with the 10^5 previously noted for increase in laser output effect and of at least 10^2 in the degree to which the effect must be improved.

Speculation regarding laser triggering of hydrogen charges [1,2,3] developed mainly as a result of the partially secret nature of laser research at CGE in Marcoussis and the fusion experiments at Limeil. The difficulties described in connection with point 1 above obviously will be encountered in any attempt to develop a fusion weapon, and those publications [6, 22b], and other available information [23], released regarding the wide-ranging activity at Limeil tend to strengthen the view that it is of the same quantity and has the same basic scientific direction as the research in the open laboratories, such as those in Garching.

6. Laser Radiation of Solid State Fusion Material in Combination With Magnetic Containment

It is possible, in principle, to check the expansion of a laser-heated particle of fusion material by superimposing an exterior magnetic field to balance the pressure in the plasma created by its own magnetic pressure. Unfortunately, even the simplest and most general calculation indicates that the magnetic field strength would then have to be 10^3-10^4 Wb/m^2, which is approximately that which one could ever hope to attain (with magnetic compression from explosives!), and further that such containment would only be effective against the direction of the imposed field, since the plasma can expand almost without hindrance along the lines of the magnetic field. One cannot, however, /13 completely discard magnetic containment solely on the basis of the pressure reasoning presented herein, since the effect of a magnetic field on a plasma is far more complex. There are indications, although these are unfortunately inadequately studied, that the plasma can itself develop a containing magnetic flux with [24, 25], and without [26], the presence of a superimposed field, and that this latter can be created in so novel a fashion, the so-called k minimum-B configuration, that the expanding plasma creates a rising magnetic pressure in nearly all directions.

There is one area in which one can definitely establish that plasma production by laser radiation of solid state fusion material will both function as expected, and, in addition, produce great advantages. It thus differs from the fusion projects previously described. This is the area concerned with the generation of a fusion plasma in any of the many types of "magnetic bottles" which were proposed long ago and which have been studied in connection with their stability and containment characteristics. The advantages have been pointed out by many, for example in reference [20], and, briefly, are as follows:

(a) the plasma produced is of extremely high purity;

(b) the presence of neutral particles (these cannot be contained magnetically) can be reduced;

(c) the difficult problem of introducing a plasma into a closed magnetic field configuration can be totally avoided (on the other hand, one does have the difficult, but soluble, technological problems of producing the particle, introducing it into the configuration, and finally obtaining a direct hit on it with the laser beam);

(d) the plasma can be provided with high initial energy;

(e) plasma characteristics, particularly its spread in time and space, can be studied with relative ease;

(f) the extreme demands on laser performance, as described in connection with inertia-contained fusion plasmas of condition $Q_{FL} = 1$, are nonexistent.

Since laser plasmas have been used for the most part in "magnetic bottles," up to this point, a few representative experiments are worth noting.

1. Haught et al [27], at United Aircraft have produced LiH plasmas /14
with a mean energy of 10^6 $^{\circ}$K in the approximately 10^{16} ions produced. This was achieved by "hanging" the radiated particle in an alternating electromagnetic field and using a laser pulse of energy 15 W-sec and a length of 15 nanoseconds. The magnetic containment was of "minimum B" and of simpler mirror

types. The plasma was found to leak out along the field lines in accordance with classic theory, and the formation of the plasma, its expansion, and containment also conformed to anticipated values.

2. Currently, Lubin, at the University of Rochester, is developing a laser system for the generation of plasma in a magnetic field configuration of the toroidal quadrupolar type. According to the calculations [28], approximately 10 percent of the generated plasma can be expected to be contained. (He also is experimenting with inertia-contained fusion plasmas by irradiating small particles of deuterium. This experiment would seem to have a connection with the "Blascon" project mentioned previously.)

3. Ascoli-Bartoli et al, of Frascati, made a report at the Novosibirsk conference in 1968, which described exceptionally attractive measurements of the effect of laser pulses of 50 W-sec and 30 nanoseconds. These were focused on chilled cylindrical deuterium particles approximately 0.2 mm in size shot from a "particle cannon" of chilled liquid helium. Preliminary measurements also had been made in a strong external magnetic field of 25 Wb/m^2. This was shown to greatly inhibit expansion. Indications also were obtained regarding certain additional magnetic containment processes, but the work was broken off at that time because of a long strike, which was in fact still in effect as of September 1970.

7. Laser Radiation of Plasmas Without Exterior Focusing

A relatively recent proposal [29] has been made suggesting the use of long wave lasers to heat plasmas to fusion. The 10μ radiation from the highly efficient carbon dioxide laser seems particularly attractive, and can be utilized in a manner such that the beam can repeatedly be passed through the plasma using a mirror and reflective system. The plasma in question may well have been formed initially with low energy but with high density and without the use of a laser. Multiple heating is necessary if the plasma is to have the pressure and densities normally assumed necessary in connection with fusion reactors, but even then the power requirements for the containing magnetic field are very high. For example, a plasma with a density of 10^{17} cm^{-3} will require a field strength of the order of 20 Wb/m^2. /15

This project is possibly one of the most interesting that has been made public in the field of controlled fusion research in the more recent past.

For example, a powerful carbon dioxide laser can provide 1000 W-sec for several dozen microseconds, and can produce a plasma with a temperature of approximately 10^7 °K in practically any type of magnetic field geometry [21]. It is an added advantage that the plasma can be built up relatively slowly, rather than being produced by the explosion of a small particle. The main problem pertains to the feasibility of attaining repeated reflections, and especially refraction, of the laser beam due to the plasma density gradients. Inconclusive experimental investigations using 3.39μ HeNe light indicate that the gradient at right angle to the beam must be significantly lower than $5 \cdot 10^{16}$ cm^{-4}. On the other hand, there is a self-focusing effect existing in laser beams which also is observable when the beam of a ruby laser has achieved a breakthrough in a gas [30]. This effect is probably significant. John Dawson [15], who was the first to propose focused laser radiation with inertia containment of fusion plasmas, has argued strongly on behalf of plasma heating by carbon dioxide lasers. The summary of his argument [21] is worth repeating verbatim:

A ten micron laser would have the following advantages: /16

(1) It could produce plasma in almost any magnetic geometry. The method of plasma production is independent of that for producing the magnetic field. The plasma β would become a controllable quantity.

(2) Interesting plasmas in the 10^2 to 10^3 eV range, density of $10^{17} \sim 10^{18}$, can be produced. These plasmas can be confined by conventional magnets of either the static or pulsed type (fields required are 30 KG to 300 KG).

(3) New situations could be investigated, such as enhanced confinement by means of a cold gas or cold plasma blanket. Self-focusing or defocusing will be important and should be investigated.

8. Immediate Problematical Questions

Despite many experiments and theories, there still is an inadequate body of available knowledge regarding the first phase of plasma formation and dynamics as a result of the use of focused laser radiation of solids. Since development is non-linear, and extremely dependent on time and space, the most reliable conformity with experiments has hitherto been attainable only with the aid of dimensional analytical treatment [31, 32], in plane geometry of one dimension. Sophisticated theoretical models [34, 35] have been studied at Garching and compared with experiments [35]. Non-linear electrodynamic coupling, essentially a form of radiation pressure, between the plasma and the focused laser beam, was carried out by Hora [36] as a conceivable mechanism for plasma containment, but this thinking has been disputed [37] based on the findings of a quantitative scrutiny of the two forces involved.

As already noted, the output energy from current pulsating glass and ruby lasers is several orders of magnitude too small to achieve an exothermic fusion process by focused radiation on particles of fusion materials. The possibility can, however, not be foreclosed that the extreme demands on laser performance can be reduced if the particles are provided with a suitable tamper and if the same demands could be reduced (or increased!) by better understanding of the initial stages during radiation [23]. Another possibility, and one that was not discussed at the Rome fusion conference, is the /17 development of new laser types with much higher optical energy density. Extremely high figures have been mentioned for solutions of certain colors [38]; $2 \cdot 10^5$ W-sec should, in theory, be releasable from 1 liter at 1 μ sec. Optical pumping should, according to this same proposal, take place through radiation from a surrounding layer of argon gas which would be heat-charged to $10\text{-}50 \cdot 10^3$ ^oK. A noteworthy part of the proposal concerns the optical pumping method, the "argon bomb," because laser systems hitherto have been considered unsuitable for use as parts of a nuclear weapon because of their large dimensions, and their electrical power demands.

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/18

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